CLIVAR

The Principal Research Areas

D3: Atlantic Thermohaline Circulation

Goal:
Improving the description and understanding of decadal to centennial variability and the possibilities of rapid climate change associated with the Atlantic thermohaline circulation.

Introduction

The oceanic heat transport in the Atlantic Ocean has an obvious and well-known impact on climate. Most of the heat transport in this basin is a consequence of the warm-to-cold water conversion associated with the thermohaline circulation. Fig. 1 shows the main northward flowing warm water routes and the cold deep southward return flows that form the North Atlantic thermohaline circulation. To the extent that variations of the thermohaline circulation on decadal-to-centennial time scales lead to changes in SST and ocean heat transports, they are therefore of direct interest to CLIVAR DecCen. Furthermore, as the transport of carbon by the Atlantic thermohaline circulation plays a significant role in the global carbon budget, thermohaline circulation variations may contribute to changes in the oceanic carbon transport and hence indirectly affect the atmospheric CO_2 content (Fig. 6).

Main Currents in the North Atlantic

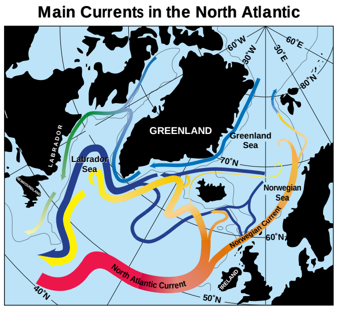


Fig. 1: An oceanic roundabout. As warm ocean currents in the subpolar gyre gradually cool, they warm Europe and may trigger seesaws in climate (McCartney et al., 1996, Oceanus, 39, 19-23).

Observing Needs

Sustained measurements and process studies are needed to explore and understand the role of the thermohaline circulation in natural climate variability and anthropogenic climate change. Photos: middle: CTD measurements in the North Atlantic (courtesy of G. Kruspe); lower left: ADCP launch; lower right stormy conditions (both courtesy of NOAA/PMEL), upper right: float deployment (courtesy NOAA/AOML)..

Repeated observations

The World Ocean Circulation Experiment (WOCE) has established an observational base of the present state of the global water mass distribution and circulation. For CLIVAR, a continuous measurement programme to observe and document the future interannual to decadal changes of the major water masses and the thermohaline circulation needs to be established. An important factor in the source regions of water mass transformation are the fields of atmospheric fluxes which still have large errors and hence augmented observing systems are needed.

Recommened specific observational programmes

- **Watermass and current sections at crucial latitudes**
- **Northern ice and freshwater import**
- **NADW export array**
- **Inventories of intermediate and subtropical mode water changes**
- **Flux fields**
- **Documentation of climate change response**

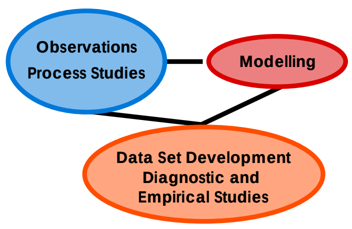
The observational programme to meet D3 requirements will have considerable common elements with that for D1 and joint planning and implementation of the field programme is essential.

Specifically designed process studies

In order to make modelling more realistic and to improve the potential for prediction, studies on the following crucial processes need to be carried out:

- **water mass transformation and its relation to the variability of the thermohaline circulation;**
- **role of the equatorial belt in interhemispheric communication of the variability of the thermohaline circulation;**
- **deep to surface layer water mass modifications**
- **subgrid-scale processes for improved parameterisation;**
- **interbasin exchange**

Programme Elements



Overarching objectives

The main objectives of a programme investigating the role of the Atlantic thermohaline circulation in DecCen-variability should then be as follows:

1. to determine the space-time characteristics of past DecCen variability that may be related to thermohaline circulation variations, with a special focus on the last 6000 years, the time interval when glacial ice sheets had disappeared and when forcings were comparable to those acting today. This would allow to put the variability of the last millennium within a longer context which is necessary to encompass the time constant of the global ocean circulation which is larger than 1000 years;
2. to determine the sensitivity of the thermohaline circulation to changes in the surface fluxes;
3. to determine the conditions under which sudden transitions of the thermohaline circulation to another state may occur;
4. to understand those oceanic processes which are critical for the dynamics of thermohaline circulation changes;
5. to investigate the coupling mechanisms between the thermohaline circulation, the wind-driven gyres, and the atmosphere;
6. to establish the degree of predictability arising from the influence of thermohaline circulation variations on atmospheric climate;
7. to investigate the sensitivity to changes in interbasin exchanges.

Data Set Development, Diagnostics and Empirical Studies

The existing instrumental record, although sparse in wide regions of the Atlantic, has already yielded in the past few years through innovative analysis techniques, a wealth of information on decadal variability of the large scale water masses, and more is expected from the reanalysis of these observations. Coral records, tree rings and ice cores from the Greenland ice-cap also can provide proxy records for determining past variability. The analysis of existing data sets along with ongoing and planned reanalysis efforts, and analysis and diagnostic of model output are essential tools for the investigation of the variability of the thermohaline circulation.

- **Data sets on water mass and thermohaline circulation variability**
- **Reanalysis of the instrumental record**
- **Model analysis**
- **The paleoclimatic record**

Sudden Changes in the Thermohaline Circulation

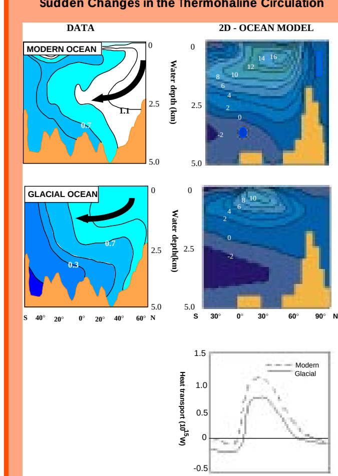


Fig. 2: Left: reconstruction of the $d^{13}C$ changes across the Atlantic ocean for the modern period (upper panel) and the Last Glacial Maximum (LGM, lower panel); adapted from Duplessy et al., 1988, Palaeoceanography, 3, 343-360.

Right: contour of the mean annual meridional overturning stream-function in the Atlantic basin for the modern conditions (upper panel) and the LGM (intermediate panel) calculated by the 2-D Louvain - La - Neuve ocean model (Fichefet et al., 1994, Nature, 372, 252-255). The lower panel shows the mean annual meridional heat transport computed for the present and LGM boundary conditions.

Modelling

Long integrations with coupled models are needed to study the space-time characteristics of model internal variability. Proper representation of the small-scale processes in the ocean component of climate models is critical for the simulation of climate change on decadal or longer time scales because the dynamics and in particular the variability of the thermohaline circulation is controlled by 'sub-scale' processes.
In order to understand and quantify the role of thermohaline circulation variations, it will be necessary to focus CLIVAR modelling activities on several aspects of the thermohaline circulation dynamics which are listed below.

- **Sudden transitions**
- **Multiple equilibrium states**
- **Sensitivity to atmospheric fluxes**
- **Resolution and parameterisation of climate-relevant processes**
- **Predictability**

Results from Modelling Studies

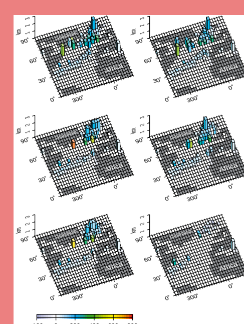


Fig. 3: North Atlantic convection patterns for six equilibrium solutions (all except bottom left having identical surface forcing) of the global ocean model by Rahmstorf (1995, Nature, 378, 145-149) which has been coupled to a highly simplified model of atmospheric heat transport. The height of the column indicates the depth of convection, and the shading indicates the amount of heat (in Wm^{-2}) lost by the ocean during convection. The upper two states have convection in the Labrador Sea, and a meridional overturning of 20 Million $m^3 s^{-1}$.
The middle two panels have no convection in the Labrador Sea, and a reduced meridional overturning of 16 Million $m^3 s^{-1}$. The bottom right panel shows a state without deep convection where the overturning circulation is collapsed > 3 Million $m^3 s^{-1}$.

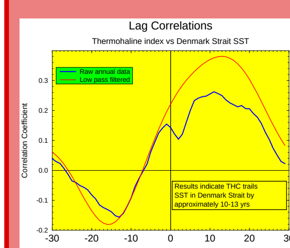


Fig. 4: Lagged correlations between the time-series of SST in the model Denmark Strait and the intensity of the thermohaline circulation in the model North Atlantic. The positive values at lag +10 indicate that the variations in the intensity of the thermohaline circulation trail the anomalous Greenland Sea SST and SSS anomalies by approximately 10 years. In the model, the surface fresh water anomalies propagate through the East Greenland current into the region of the Labrador Sea. There, the anomalous surface fresh water inhibits the convective exchange of heat between the atmosphere and the subsurface of the ocean, thereby weakening the thermohaline circulation (courtesy of T. Delworth).

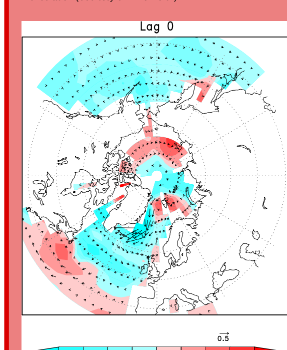


Fig. 5: Anomalous surface currents (vectors) and sea surface salinity (SSS; shading) at the time of coldest temperatures in the Denmark Strait. Prior to the phase of the oscillation depicted here, there was a buildup of fresh water in the Arctic. This fresh water then exited the Arctic through Fram Straits and the East Greenland Current, leading to an anomalously fresh Greenland Sea. Associated with this was a strengthening of the model East Greenland current (Delworth, T.S., S. Manabe, R.J. Stouffer, 1997, Geophys. Res. Lett., 24, 257-260).

The Atlantic Thermohaline Circulation

- A key Element of the Global Oceanic Circulation -

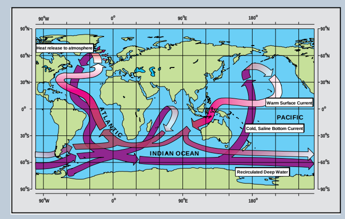


Fig. 6: Schematic diagram of the global ocean circulation pathways, the 'conveyer' belt (after W. Broecker, modified by E. Maier-Reimer).

The Thermohaline Circulation and the NAO

- A coupled Phenomenon ? -

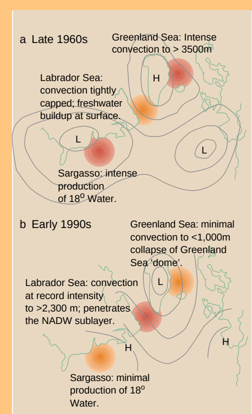


Fig. 7: Depiction of the changes in the distribution of winter convective activity in the North Atlantic during contrasting extreme states of the North Atlantic Oscillation (NAO). The main convective centres are in the Greenland, Labrador and Sargasso Seas.
a) Represents the 'low-index' NAO conditions of the late 1960s; b) the 'high-index' state of the early 1990s. A representative mean pressure anomaly field is indicated for each case. 'Mode waters' are formed in winter at each of the three sites, are vertically homogeneous, and through horizontal spreading provide a mechanism for carrying the signal of climate change throughout the North Atlantic basin. '18° Water' is the mode water of the Sargasso Sea. NADW is North Atlantic Deep Water. The Greenland Sea 'dome' is the place where a cyclonic basin circulation brings dense water closest to the surface, promoting convective instability (Dickson R., 1997, Nature, 386, 649-650)

Planned Activities

Atlantic Climate Variability Experiment

A multinational basin-scale experiment for the Atlantic, the Atlantic Climate Variability Experiment (ACVE) has been proposed. This experiment is highly relevant to all three Atlantic PRA's of CLIVAR (D1-D2-D3). ACVE has been conceived as a major contributor to the CLIVAR programme. As such, ACVE will provide real time assessments of the state of the Atlantic Ocean in relation to climatic variations of the atmosphere. These will be of great utility to research programmes which seek to understand the role of ocean biogeochemistry in climate, and the impacts of climate variability on fisheries. Therefore strong connections exist with many other on-going or planned programmes.
The specific objectives of the Atlantic Climate Variability Experiment are to:

- Describe and model coupled atmosphere-ocean interactions in the Atlantic sector, quantify their influences on the regional and larger scale climate system, and investigate their predictability.
- Assemble a quantitative historical and real time data set that may be used to test, improve and initialize models of coupled Atlantic climate variability.
- Investigate the sensitivity of the meridional overturning circulation of the ocean to changes in surface forcing and assess the likelihood of abrupt climate change.

Cross linkages within other CLIVAR PRA's

This research project is closely related to the following CLIVAR PRA's:

D1
The North Atlantic Oscillation

D2
Tropical Atlantic Variability

D5
Southern Ocean Climate Variability